Gravitational strings. Do we see one?

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Abstract

I present a class of objects called gravitational strings (GS) for their similarity to the conventional cosmic strings: even though the former are just singularities in flat spacetime, both varieties are equally "realistic", they may play an equally important cosmological rôle and their lensing properties are akin. I argue that the enigmatic object CSL-1 is an evidence in favor of the existence of GS.

Introduction

The objects discussed below — the gravitational strings — have much in common with the conventional cosmic strings. So, I begin with a brief reminder of a few key facts about the latter [1].

The appearance of the cosmic strings in the early universe is usually explained as follows. Suppose, after the universe had cooled below some critical temperature, a complex scalar field ϕ appeared with the Mexican-hat potential

$$L = \partial_\mu\phi\partial^\mu\bar{\phi} - \tfrac{1}{4}(\phi\bar{\phi} - a^2)^2, \qquad a > 0.$$

One expects the field to take the minimal energy value, i. e., $\phi = ae^{i\sigma}$ with arbitrary $\sigma \in \mathbb{R}$. But the evolutions of the field in different regions are *uncorrelated* and this can make the process energetically prohibited even though *locally* it is energetically favourable. Indeed, if the field happened to develop a non-zero winding number on some loop C, see figure 1, then it cannot be extended to a surface enclosed by C without vanishing in some point. Clearly, the energy density around that point will be non-zero. This fact is purely

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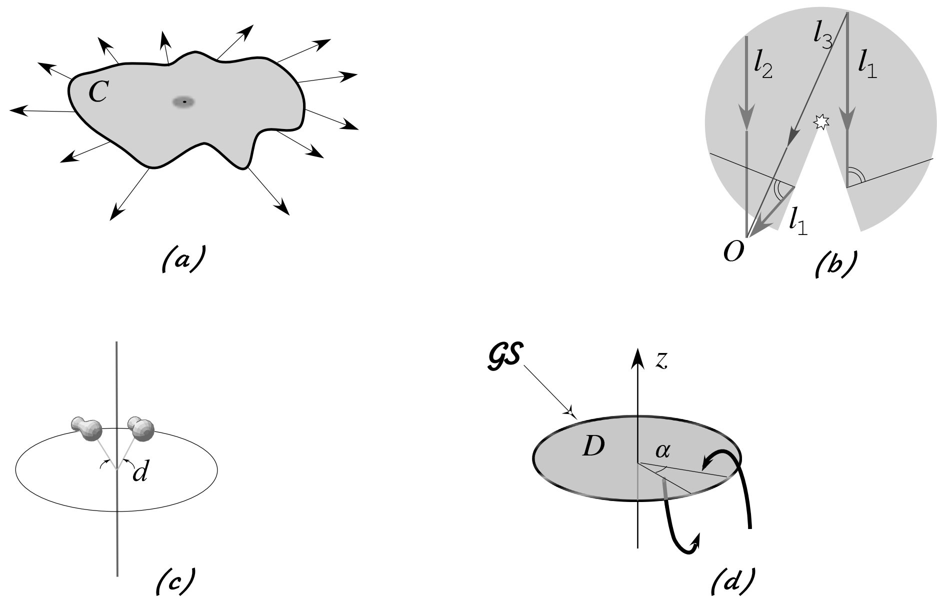

Figure 1: a) The arrows represent complex numbers, not 3-vectors. b) The ray l_1 is parallel to l_2 and starts from the same point as l_3. Still, all three meet in O. c) The images of a non-pointlike source are rotated w. r. t. each other. d) What looks as two thick curves is, in fact, a single continuous curve.

topological, so if we continuously deform the loop or the surface, the point with the non-zero energy density will persist. So, the field configuration is an endless thin tube. The tube is stable: even though it is surrounded by vacuum, it cannot dissolve for the topological reasons discussed above. It is such tubes that are called (material) cosmic strings.

The importance of cosmic strings, as well as their most promising (from the observational point of view) manifestation stem from their — quite unusual — gravitational fields. The universe with a straight endless string is believed to be described — *at large* ρ — by the spacetime

$$\begin{gathered} \mathrm{d}s^2 = -\mathrm{d}t^2 + \mathrm{d}z^2 + \mathrm{d}\rho^2 + \rho^2\mathrm{d}\varphi^2, \\ t, z \in \mathbb{R}, \quad \rho > 0, \quad \varphi = \varphi + 2\pi - d, \quad d \in (0, 2\pi). \end{gathered} \tag{1}$$

It is often convenient to represent the sections $t = \mathit{const}$ of this spacetime as the results of the following surgery: a dihedral angle having the z-axis as

its edge is cut out of the Euclidean space $\mathbb{E}^3$ and the half-planes bounding it are glued together (with no shift along the axis). Since the axis cannot be glued back into the spacetime, there is a singularity now "in its place". This singularity (often called conical) is sometimes associated in folklore with the string itself.

When a string moves through the cosmological fluid it leaves a wake behind it: as is seen from Fig. 1b, two *parallelly* moving galaxies may nevertheless collide after a string has passed between them — a phenomenon of obvious importance to cosmology. On the other hand, two light rays emitted from the same source may, for exactly the same reasons, come to an observer from different directions, see Fig. 1b. Thus, a string acts as a gravitational lens producing multiple images of a single object, see Fig. 1c.

1 Gravitational strings

Now let us consider the purely gravitational case.

At the end of the Planck era the classical spacetime had emerged and started to expand obeying the Einstein equations. By the time it could be confidently called classical it was practically flat (by Planck standards, anyway), so we can speak of emergence of a flat spacetime. One can think, however, that remote regions evolved uncorrelatedly and the locally fovourable process of becoming Minkowskian might be impeded by some *global* obstacles. For example, a circle lying in a newborn (non-simply connected) flat region might happen to be too short (or too long) for its radius of curvature. Exactly as with matter fields such obstacles would give rise to singularities. This time, however, those would be true *geometric* singularities and of a rather unusual kind at that: the spacetime is flat, so the singularities are not associated with infinite curvature, or energy density, etc. It is such singularities — more precisely two-dimensional[1] singularities in flat spacetime — that I call gravitational strings (GS).

An example of a GS is the singularity in the spacetime (1) (the latter must be understood this time literally, not as an approximation valid at large ρ). Other examples can be obtained, if one of the mentioned half-planes, before it is glued to the other, is shifted along the z-axis [2], or the t-axis [3], or, finally, is boosted in the z-direction [4]. The resulting spacetimes are quite different,

[1]The meaning of the term "two-dimensional" is hopefully clear intuitively. For a rigorous definition see [5].

but each contains an infinite straight gravitational string at rest. Recently the list was supplemented by more curious species [5] including spiral strings, rotating straight strings, and even closed strings. The (sections $t = const$ of the) latter are obtained — or, rather, are described — as follows. Remove the closure of the circle

$$D: \quad x^2 + y^2 < 1$$

from the Euclidean space $\mathbb{E}^3$, rotate one of the banks of the thus obtained slit (either is a copy of D) by some $\alpha \neq 2\pi$ w. r. t. to the z-axis, and, finally, glue the banks together. The missing circumference $\operatorname{Bd} D$ (it cannot be glued back into the space) is a GS, see Fig. 1d.

Thus, a new class of objects is introduced — the gravitational strings. They have much in common with the conventional (matter) cosmic strings: both species are equally "realistic" (the reasons to believe in their existence are much the same), equally important cosmologically (both leave wakes) and have similar lensing properties. Still, in some respects they are quite different. In particular, the relevant spacetime being *empty*, the evolution of a gravitational string, its form, its gravitational field, etc. have nothing to do with properties of any matter field, with the Nambu action, and so on.

2 Observations

Whether gravitational strings do exist is, ultimately, to be answered by observations. So, what would one expect to observe if there is a circular (this form is chosen, because it is easier to imagine the formation of a *finite* object) string of a galactic size located far enough from the Earth and tilted by an angle $\theta \sim 1$ (no fine tuning!) relative to the line of sight?

In analyzing this situation it is convenient to view the "real" space as the Euclidean space $\mathbb{E}^3$ (minus circumference) where light rays are, as usual, straight lines, but where one additional rule holds: if a ray meets D, its extension beyond D is rotated by α w. r. t. to the z-axis. So, to determine what the observer sees if there is a bright source S near the string, rotate S by α obtaining thus a "fictituous" source S', see Fig. 2a. If one of the straight lines — OS or OS' — meets D and the other does not, then the observer will see both images S and S', otherwise only one of them. Note that the two images are not *exactly* same: because $\theta \sim 1$, they are rotated w. r. t. to each other. In summary: if there is an appropriately located galaxy, see Fig. 2b, then what we must see is two close galaxies with similar

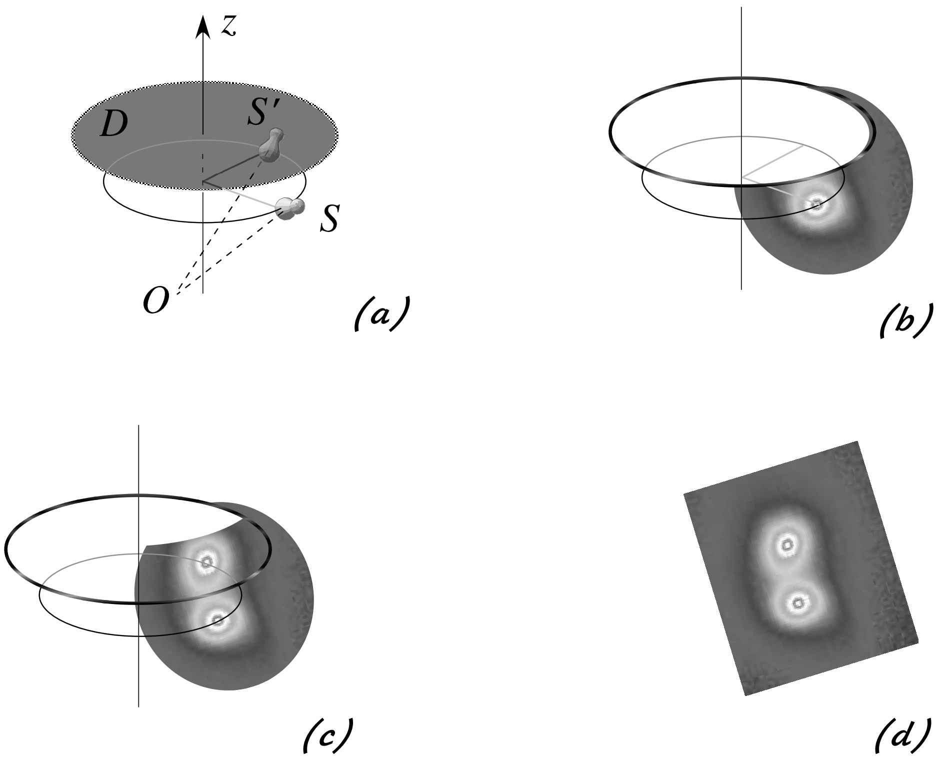

Figure 2: a) O sees two similar images. b) A single "real" galaxy. c) Its image in the presence of a loop GS. d) The Hubble Space Telescope image of CSL-1.

spectra, or in other words, two images of the same galaxy as seen from different angles, see Fig. 2c.

Remarkably, such a picture *is* observed [6]. A pair of galaxies called CSL-1 are 1.9 arcsec separated and have the same spectra identical at 98% confidence level. This strongly suggests that what we see (a HST image is shown in Fig. 2d) is, in fact, two images of the *same* galaxy. The isophotes are not distorted, so the lensing presumably does not involve a strong gravitational field, which rules out a galaxy, or a conventional loop string as the lens. At the same time it is not a straight infinite string, because no more pairs have been found in that region of the sky, while calculations predict at least 9 ones [7]. It seems, thus, quite natural to interpret CSL-1 as an observational proof of the existence of gravitational strings.

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